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RECORD PULSED POWER DEMONSTRATION OF A 2μm GaSb-BASED OPTICALLY PUMPED SEMICONDUCTOR LASER GROWN LATTICE-MISMATCHED ON AN AlAs/GaAs BRAGG MIRROR AND SUBSTRATE (POSTPRINT)

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An optically pumped semiconductor laser resonant periodic gain structure, grown lattice-mismatched on an AlAs/GaAs Bragg mirror, exhibits a peak pulsed power of 70 W when pumped with a pulsed 1064 nm neodymium doped yttrium aluminum garnet laser.

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Record pulsed power demonstration of a 2 μm GaSb-based optically pumped semiconductor laser grown lattice-mismatched on an AlAs/GaAs Bragg mirror and substrate

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An optically pumped semiconductor laser resonant periodic gain structure, grown lattice-mismatched on an AlAs/GaAs Bragg mirror, exhibits a peak pulsed power of 70 W when pumped with a pulsed 1064 nm neodymium doped yttrium aluminum garnet laser. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3212891]

Optically pumped semiconductor disk lasers (OPSL) or, equivalently, vertical external cavity surface emitting semiconductor lasers (VECSEL), are emerging as novel sources of high-power, high brightness IR, mid-IR, visible, and UV light. Record powers up to 30 W in an essentially TEM_{00} have been demonstrated in the IR band by Coherent.[1] Using intracavity second harmonic generation, spectrally narrow multiwatt outputs have been demonstrated at green[2] and yellow-orange[3] wavelengths in TEM_{00} beams. Direct generation of red light at 670 nm with powers close to 0.5 W has also been demonstrated.[4] These VECSEL structures were grown using InGaAs or InGaPAs quantum well (QW) stacks grown on AlGaAs/AlAs Bragg mirrors. Extension of these structures to the mid-IR, requires growth of InGaSb QW stacks on AlGaSb/GaSb Bragg mirrors. The latter have been employed to demonstrate 3–5 W VECSEL lasing between 2 and 2.3 μm.[5] Two fundamentally different wafer growth modes have been employed in all cases. The most common approach is to grow the distributed Bragg reflector (DBR) stack directly on the substrate (GaAs or GaSb) followed by growth of the resonant periodic gain (RPG) QW stack.[6] Thermal management of these devices requires that a transparent SiC or single crystal diamond intracavity heat spreader be bonded directly to the top epitaxial surface. An alternative approach that has demonstrated the highest powers to date is to grow the RPG multi-QW stack directly on a GaAs substrate, followed by the DBR.[7] This approach requires that the GaAs substrate be completely etched away after mounting on a chemical vapor deposition (CVD) diamond heat spreader. The resulting semiconductor microcavity consisting of RPG gain section and DBR is extremely thin and can be cooled directly from the bottom of the chip.

In this letter, we introduce a growth method not previously used and demonstrate a peak pulsed power of 70 W at 2 μm. Our goal is to retain the AlGaAs/GaAs DBR and GaAs substrate but to grow an antimonide RPG stack consisting of InGaSb quantum wells embedded in AlGaSb barriers on the latter structure. The AlGaAs/GaAs DBR is grown independently on a GaAs substrate using a metal oxide CVD reactor. This mirror structure is loaded in a molecular beam epitaxy (MBE) reactor and the final RPG gain section is grown next using an interfacial misfit array (IMF) technique[8] to offset the lattice mismatch. Details of the growth and wafer characterization will be published elsewhere. We chose this route because of the lower thermal impedance of the AlGaAs/GaAs mirror relative to an AlGaSb/GaSb mirror and our recent observation from spectroscopic studies show that bulk GaSb exhibits evidence for deep-level defects, that can act as significant loss sites around 2–2.5 μm. The entire VECSEL subcavity was designed using a rigorous microscopic physics model for the active RPG structure and growths were validated against a software tool based on the latter model.[9]

This OPSL/VECSEL structure, with a III-Sb active region grown on AlGaAs/GaAs DBRs without the use of thick metamorphic buffers, is a different design than any previous structures. The effective lattice mismatch of 7.78% between the DBR and the active region is accommodated by the IMF growth mode. The complexities involved in the growth of such a structure are significant and hence we have chosen to pump the laser at subthermal levels using pulsed pumping instead of continuous pumping which would require additional processing for thermal management schemes. We carried out full spectroscopic analysis of the grown structure and compared measured room temperature OPSL chip reflectance, edge and surface photoluminescence (PL) spectra against the microscopically calculated designs. (PL peak location and intensity were sensitive to growth temperature and Sb flux in the MBE reactor.) The measured data showed good agreement with the designs but the chips were expected to lase under subthermal pulsed conditions, so we used a pulsed neodymium doped yttrium aluminum garnet (Nd:YAG) laser at 1064 nm for the pump source. The pulse lengths were typically 300 ns, and the duty cycle was kept very low to avoid heating as much as possible. (Since the

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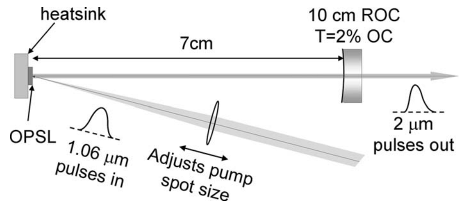

FIG. 1. OPSL schematic layout.

OPSL's active quantum wells were on top of the substrate, which is a poor heat conductor.)

Figure 1 shows the experimental arrangement. The pump laser is a diode-pumped Nd:YAG laser that is continuously pumped and repetitively Q-switched by an acousto-optic Q-switch. The repetition rate of the laser is 1 kHz, and typical pulse lengths are 300 ns, with peak power variable between 0 and 1.2 kW. Pulse energies varied between 0 and 0.4 mJ, and typical average pump power was 200 mW. The laser beam was focused by means of a 12.5 cm focal length lens onto the OPSL chip under test. The pump beam was nominally TEM_{00}. A linear cavity was used for the OPSL laser. Two different OPSL chips from the same wafer were evaluated. One chip was antireflection (AR) coated at the lasing wavelength of 2 μm, and the other was uncoated. A 2% transmitting, 10 cm radius of curvature output mirror was used for the AR coated chip, and a 4% transmitting, 10 cm radius mirror was used for the uncoated chip. In both cases, the output mirror was spaced 7 cm from the OPSL chip, giving a fundamental mode radius of 178 μm at the lasing wavelength of 2 μm. The diameter of the pump spot was varied by varying the spacing between the lens and the OPSL chip. For the highest power experiments, the pump spot size was much larger than the OPSL fundamental mode size, and the output was thus highly multimode.

Figure 2 shows the peak output power at 2 μm for the two OPSL chips. The AR coated chip was operated with the pump spot size matched to the resonator mode and also with a much larger pump spot size. For the smaller spot size of approximately 350 μm, which was approximately matched to the resonator mode, the threshold was lowest, at about 19 W. The initial slope efficiency is around 15%, but the output power saturates at 8 W due to lack of cooling. The other curve for the AR coated chip is for a pump spot size of 725 μm, which is about twice as large, hence the pump area is four times as large. The measured threshold for the smaller pump spot size is 19.5 W, while the measured threshold for the larger pump spot is 72 W due to the larger pump spot size. The ratio of thresholds is approximately the ratio of the pump spot areas. We observed some damage at the highest pump power for this chip. Due to the larger pump spot area in the second case the OPSL runs on multiple lateral modes. The third curve is for the uncoated chip. In this case, the microcavity resonance between the DBR and the uncoated chip surface forms a resonant structure that increases the internal electric field and hence gives greater gain. We found a 4% mirror gave higher output in this case, and maximum peak power is 70 W. The saturation at high powers is due to the fact that as we increased the pump power, the pump pulse length became shorter, and the OPSL buildup time became a factor.

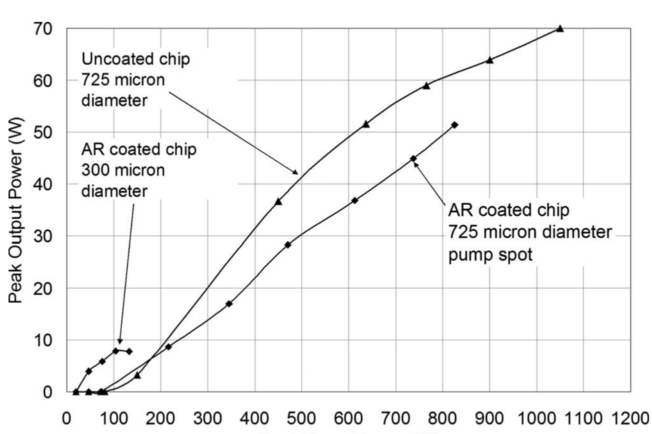

FIG. 2. 2 μm OPSL peak output power.

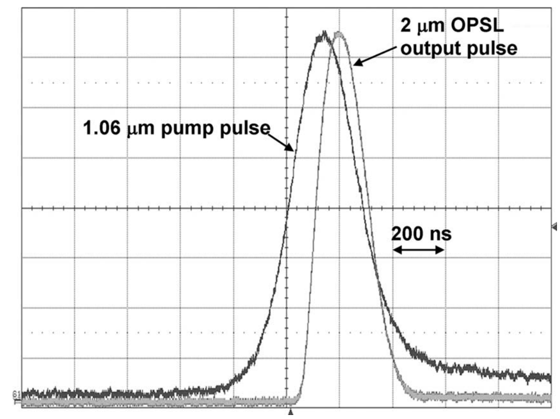

FIG. 3. Pump and OPSL pulse shapes.

Figure 3 shows the temporal pulse shapes of the pump and the 2 μm OPSL output under typical operating conditions. The pump was measured with a fast silicon photodiode and the OPSL with an InGaAs detector. The pump pulse is essentially Gaussian shaped temporally. The pump peak power was calculated by measuring the average power of the pump and dividing by the repetition rate and the pulse width at half-maximum. The OPSL turns on near the peak on the leading edge of the pump pulse. The threshold pump power was calculated by turning the pump power down until the OPSL just oscillated and calculating the pump power as above. This gives a pessimistic estimate of the pump power, since the actual threshold had to occur before the peak due to build up time in the OPSL resonator. The OPSL output power was also calculated by measuring the average power and the pulse length.

The spectrum of the OPSL was measured with an infrared spectrometer and the spectrum consisted of a single peak at 1995 nm, very near the design wavelength of 2.0 μm.

In conclusion, we have designed a near infrared OPSL with an antimonide-based resonant periodic gain structure grown lattice mismatched on a AlAs/GaAs Bragg mirror, grown samples, and evaluated them under pulsed conditions. The 70 Watt peak output at 2 μm is the highest reported power to date from a near infrared OPSL.

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[1]J. Chilla, Q. Shu, H. Zhou, E. Weiss, M. Reed, and L. Spinelle, Proc. SPIE **6451**, 645109 (2007).
[2]L. Hunziker, Q. Shu, H. Zhou, D. Bauer, C. Ihli, G. Mahnke, M. Rebut, J. Chilla, A. Caprara, H. Zhou, E. Weill, and M. Reed, Proc. SPIE **6451**, 64510A (2007).
[3]M. Fallahi, L. Fan, Y. Kaneda, C. Hessenius, J. Hader, H. Li, J. V. Moloney, B. Dunert, W. Stolz, S. W. Koch, J. Murray, and R. Bedford, IEEE Photonics Technol. Lett. **20**, 1700 (2008).
[4]J. E. Hastie, S. Calvez, M. Dawson, T. Leinonen, A. Laakso, J. Lyytikainen, and M. Pessa, Opt. Express **13**, 77 (2005).
[5]J. M. Hopkins, N. Hempler, B. Rosener, N. Schulz, M. Rattunde, C. Manz, K. Kohler, J. Wagner, and D. Burns, Opt. Lett. **33**, 201 (2008).
[6]J. V. Sandusky and S. R. J. Brueck, IEEE Photonics Technol. Lett. **8**, 313 (1996).
[7]M. Kuznetsov, F. Hakimi, R. Sprague, and A. Mooradian, IEEE Photonics Technol. Lett. **9**, 1063 (1997).
[8]S. H. Huang, G. Balakrishnan, A. Khoshakhlagh, A. Jallipalli, L. R. Dawson, and D. L. Huffaker, Appl. Phys. Lett. **88**, 131911 (2006).
[9]SimuLase, from Nonlinear Control Strategies, Tucson, AZ.